Temperature dependence of surface strain damage in rf cavities

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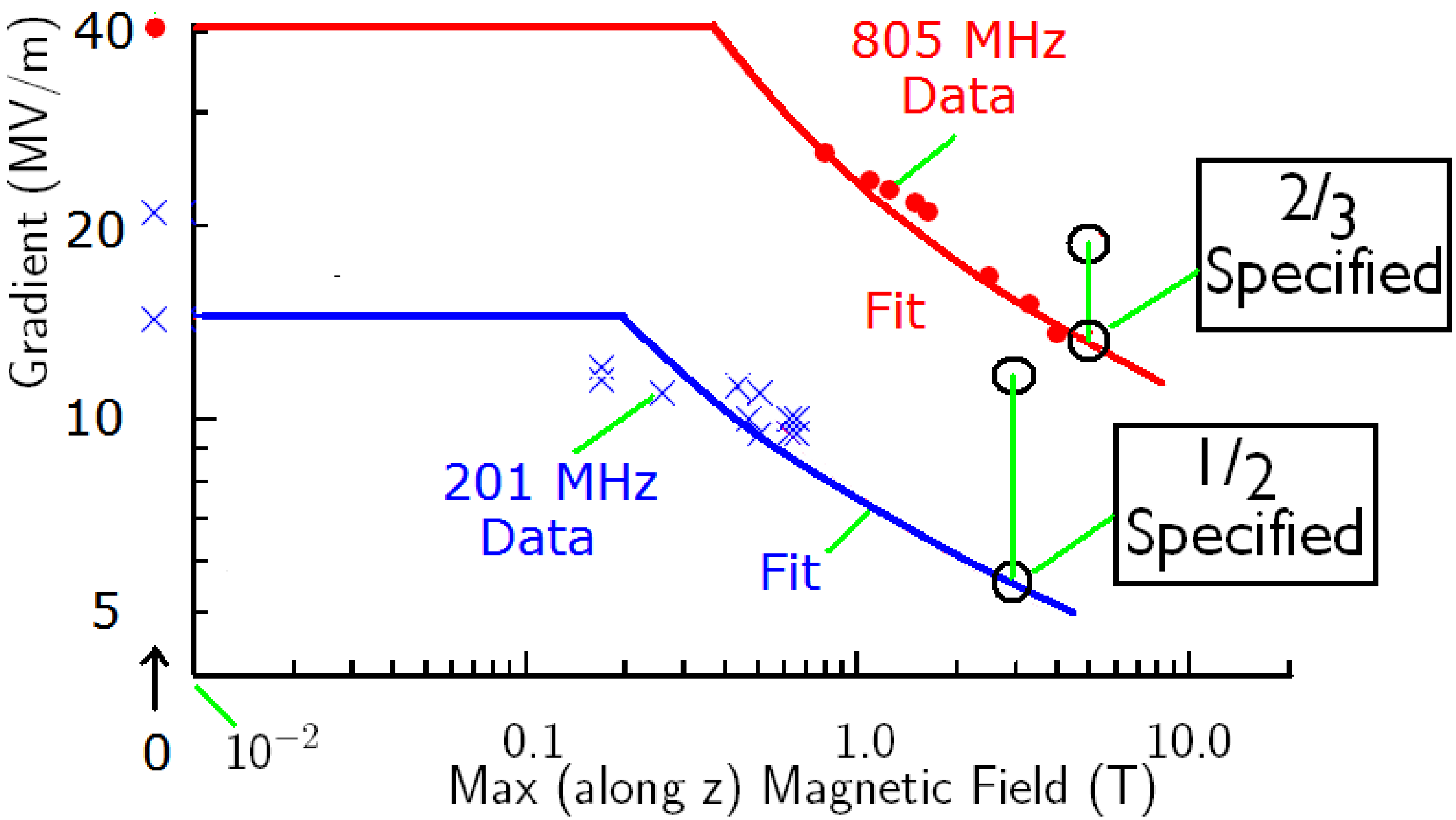
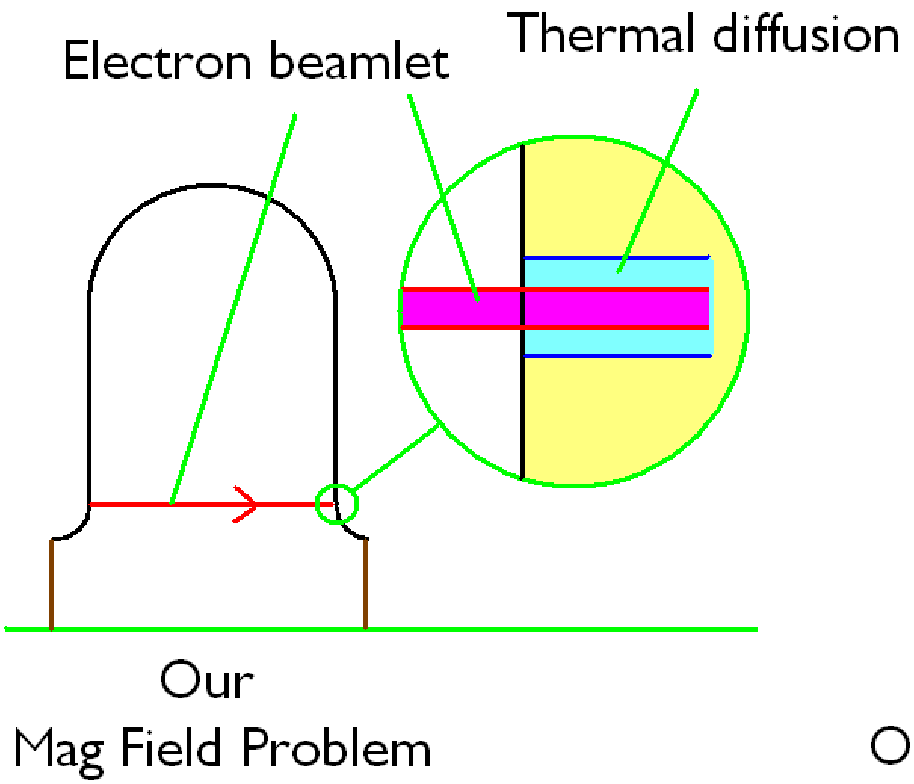
- Introduction
- Rf in magnetic fields problem
- High frequency surface damage problem
- Appendix: Assumed material parameters

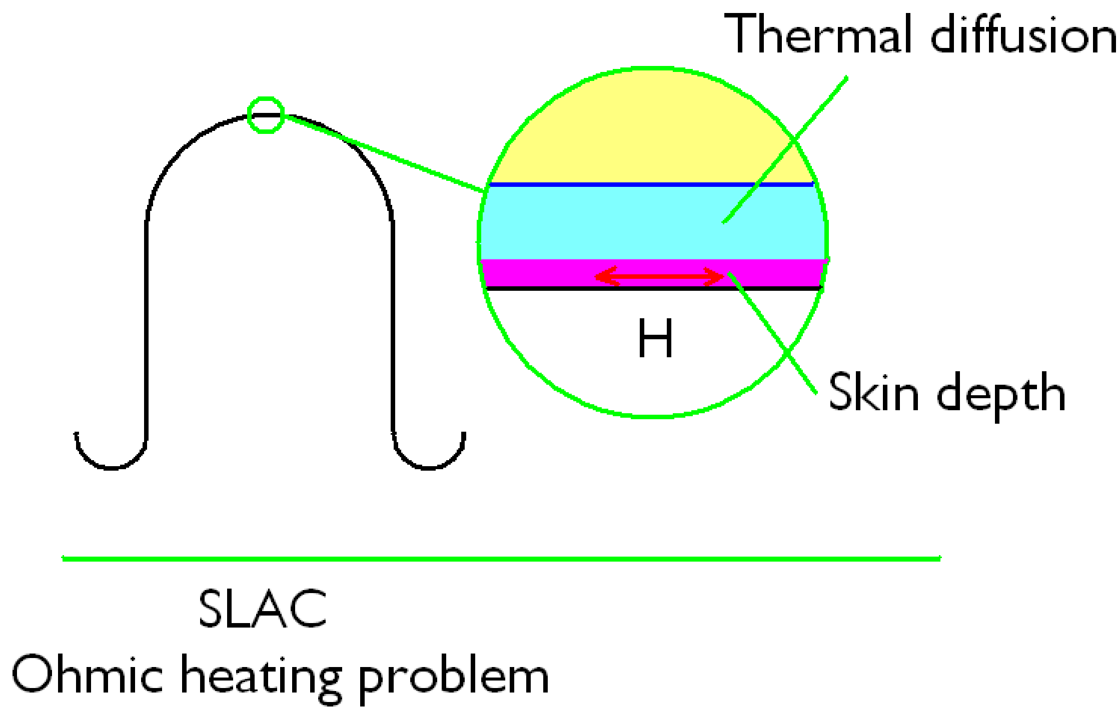
Introduction



- Cavities in specified magnetic fields do work
- But achieved fields are down by "only" a factor of ≈ 2
- Is there a way to raise the damage threshold ?

Two Related problems





- In both, damage probably caused by fatigue from repeated strains induced by heating
- In both, it should be reduced by
  - Choice of materials
  - Lower initial temperature

Choice of materials

- For both problems we seek
  - Low coefficients of expansion
  - High specific heat
  - High thermal conductivity
- For the magnetic field problem
  - Low density and resulting lower beamlet energy loss
- For the high frequency surface damage problem
  - High electrical conductivity

Materials considered:

1. Copper
2. Beryllium for its very low density and experimental lack of damage
3. Aluminum for its lower density than copper

In each case we will consider

- Very pure materials with Relative Resistance Ratios (RRR) over 1000
- Less pure materials with Relative Resistance Ratios (RRR) around 100

Problem 1) Strains due to Beamlets

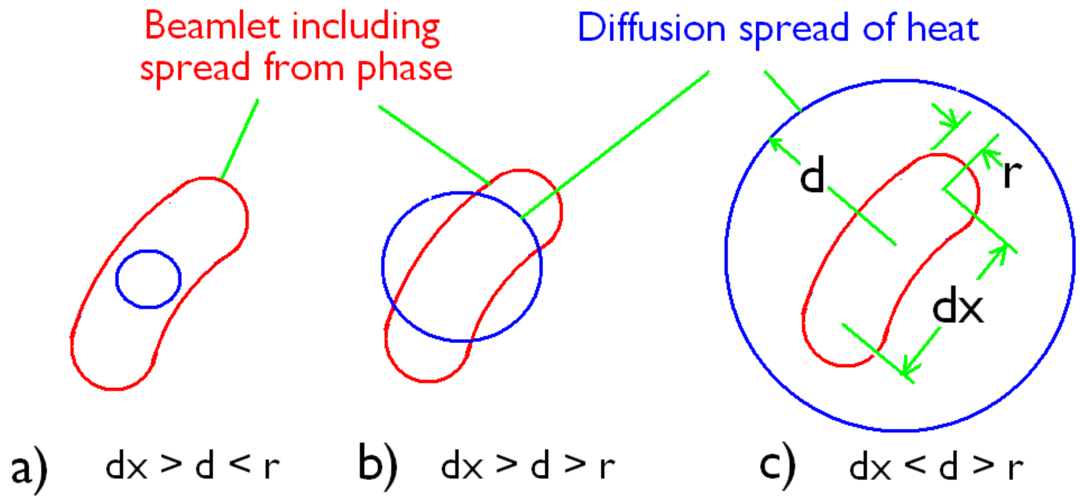
$$\Delta T \ \propto \ \frac{dE}{dx} \ \int_o^t \frac{Q(T)}{A_{beam}\ \rho\ C_p(T)} dt$$

$$S \ \propto \ \frac{dE}{dx} \ \int_o^t \frac{Q(T)\ \alpha(T)}{A_{beam}\ \rho\ C_p(T)} dt$$

Where $\alpha(T)$ is the coefficient of thermal expansion, and A_{beam} is the transverse area of the beamlet at the surface, and $Q(T)$ is a factor to include thermal diffusion that increases the transverse area where the heat is deposited

- We assume the rf pulse length t is NOT increased even when low temperatures give longer decay times τ
- This is an approximate calculation because it ignores the variations in temperature with lateral diffusion
  - It is a good approximation if $\alpha(T)/C_p(T)$ and Q(T) do not change much over the range of T in the integration
  - SLAC sees damage when $\Delta T \ \approx \ 45$ degrees starting from 273 deg. Over this range these functions do not change much and the approximation is good. It is less so at lower temperatures

Correction $Q(T)$ for thermal diffusion



$$a)\quad Q(T) \;=\; 1 \qquad b)\quad Q(T) \;=\; \frac{d(273)}{d(T)} \qquad c)\quad Q(T) \;=\; \frac{dx\ r_{beam}}{d(T)^2}$$

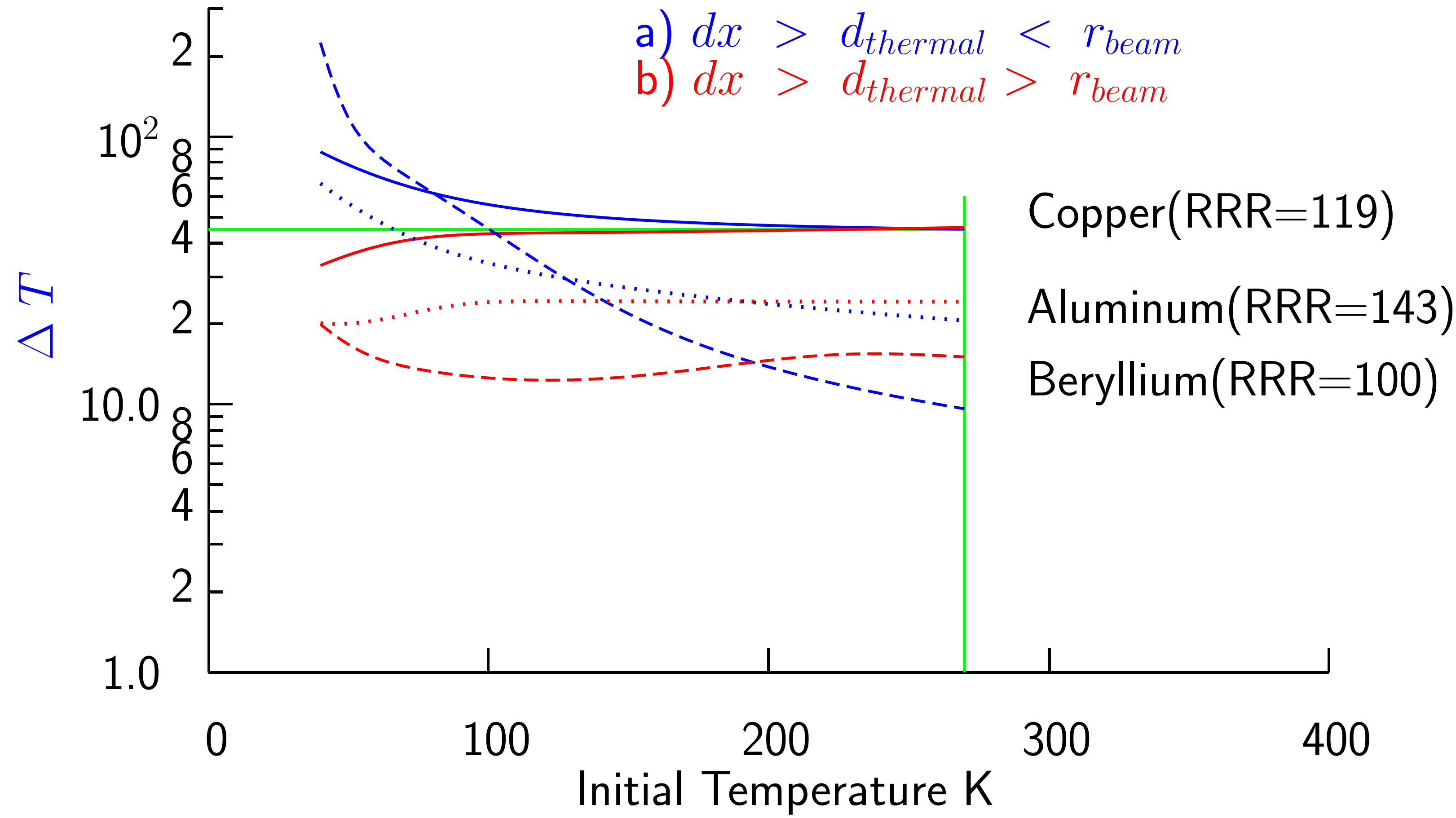
where d, the thermal diffusion length:

$$d(T) \;=\; \sqrt{\frac{K(T)\tau}{\rho C_p(T)}}$$

- Fit to data had assumed a)
- But recent simulations suggest b) more likely at 805 MHz,
- c) gives breakdown independent of B Not as observed

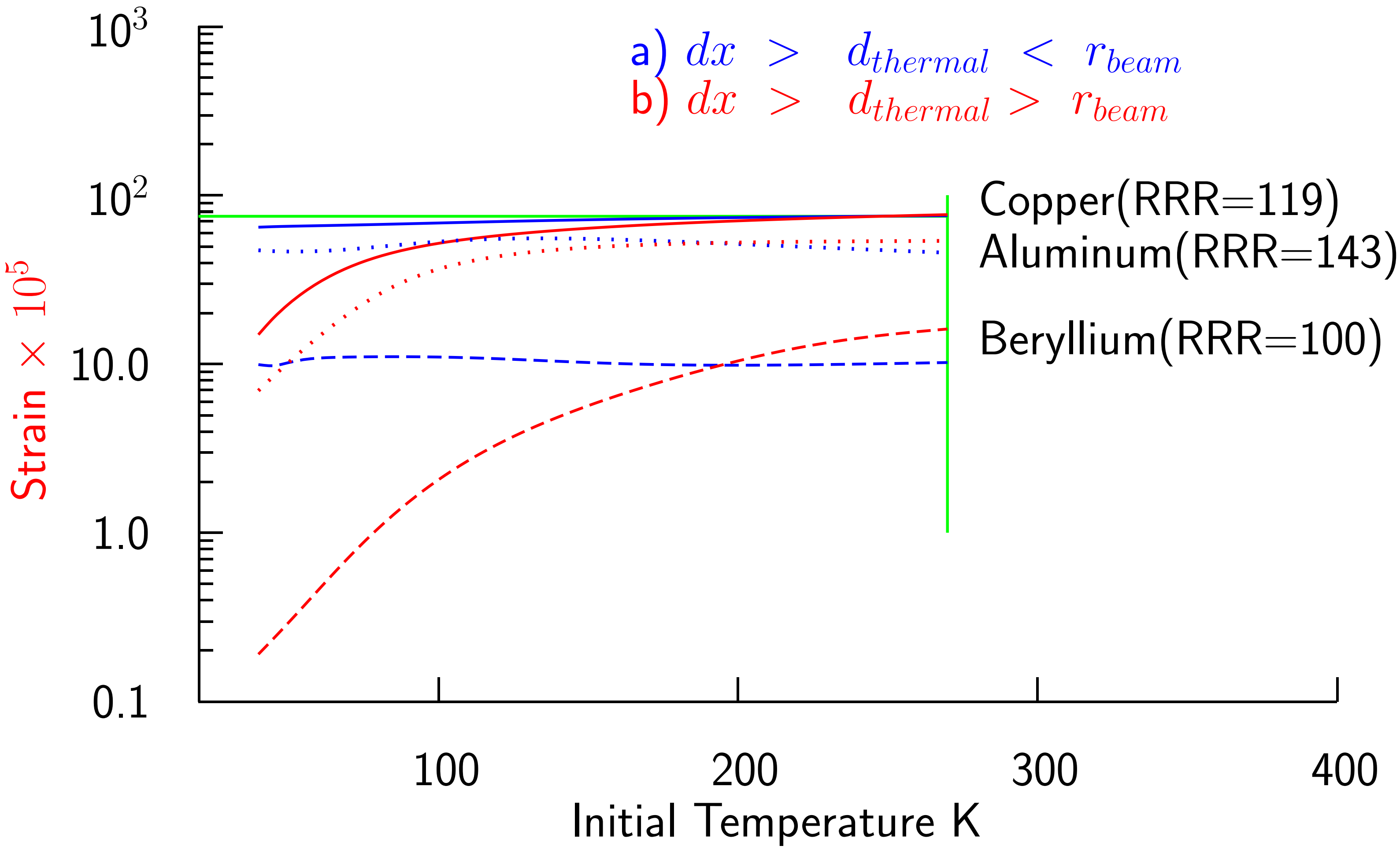
e.g. 805 MHz: for $B = 3$ (T) $\quad \mathcal{E} = 17$ (MV/m) dx=100 (μm)
d=48 (μm) r¡10 (μm)

Temperature Rises



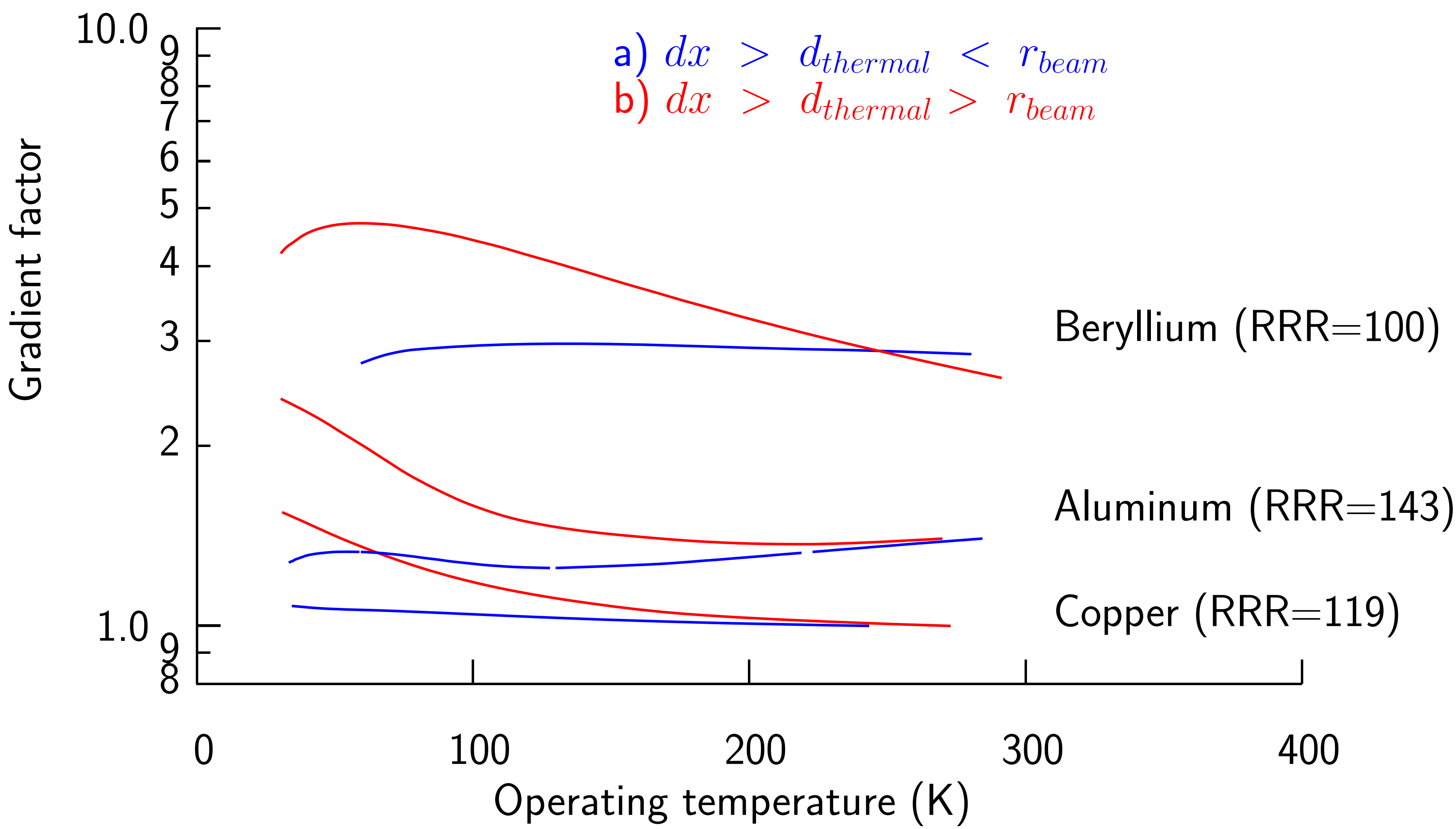
- Normalized to give ΔT of 45 degrees for Cu at room T
- This is case that caused damage in SLAC surface heating exp.

Strains



- Be has much less strain at room T
- Al somewhat less strain at room T
- In case a): no change with temperature
- cases b) and c) less strain at low T

Relative rf gradients for same strain



Observations

- At room temperature
  - Aluminum damage at 1.4 times rf gradient   Not enough
  - Beryllium damage at 3 times rf gradient   Enough
- If case a) $r_{beam} >$ diffusion length (assumed in paper)
  - No gain with lower operating temperature
- In most likely case b)
  - Gain with Copper of $\approx$ 1.3 at 70 K^o Not enough
  - Gain with Aluminum of $\approx$ 2 at 70 K^o Enough
  - Gain with Beryllium of $\approx$ 4.5 at 70 K^o Not needed

Conclusions on rf breakdown in magnets problem

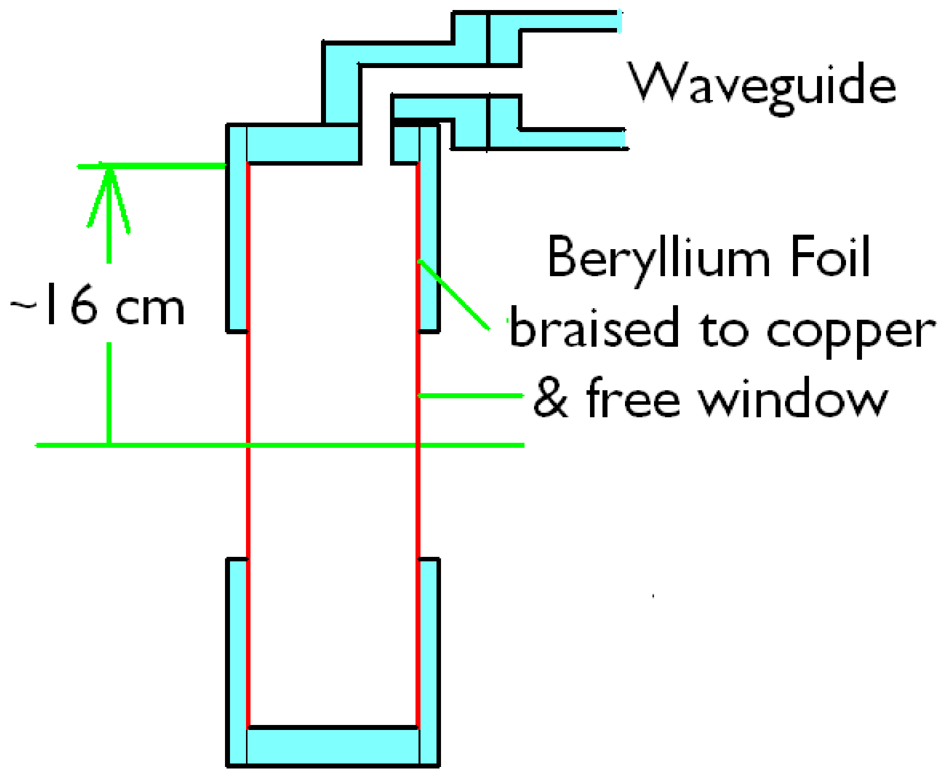
- Beryllium is the ideal material
  - Would probably solve the problem even at room temperature
  - Would certainly solve it at nitrogen temperature
- Aluminum is significantly better than Copper
  - If cold, it would probably solve the problem
  - If multipacter is a problem, a thin copper layer would be ok

Advantages over Magnetic Insulation

- Pillbox cavities have better Shunt Impedance
- Pillbox cavities give more acceleration for same surface fields
- Muon transmission is better with less rapid field changes
  - Simulations of RFOFO Guggenheim 6D cooling gives unacceptable losses
  - A Neutrino Factory front end using magnetic insulation appears difficult

Possible Experiments

1. Cool and test refurbished 805 MHz Pillbox Cavity to Nitrogen temperatures
2. Build and test an 805 MHz Al cavity at room and Nitrogen Temperatures
3. Build a Be faced 805 MHz cavity and test in 'non-flip' field
   not testable at low temperatures because of differential expansions



Problem 2) Surface rf ohmic heating

- At frequencies of, and above, 10 GHz, with normal pulse lengths, breakdown appears initiated when surface heating caused fatigue damage
- SLAC experiments show damage in soft copper when $\Delta T \geq 45$ degrees

Ohmic heating in skin depth:

$$\frac{dU}{dA} = k_1 \; H^2 \sqrt{R(T) \; f} \; dt \quad = \; k_2 \, \mathcal{E}^2 \, \sqrt{\mathrm{R(T) \; f}} \; \mathrm{dt}$$

H = local rf magnetic field, $\mathcal{E}$ = accelerating gradient, $R(T)$ = is electrical resistivity

The heat is disipated in a thermal diffusion length depth $d(T)$

$$d(T) = \sqrt{\frac{K(T)\tau}{\rho C_p(T)}}$$

$K(T)$ is thermal conductivity, ρ is the density, $C_p(T)$ is specific heat,

$$\tau = \tau_{805} \left(\frac{805(MHz)}{f} \right)^{1.5}$$

where τ_{805} is taken to be 20 μ sec.

Surface temperature and strain

- Assume rf pulse length τ not changed as a function of temperature, even though the natural "filling time" is
- Minimizes the cryogenic load from ohmic losses in the cavities

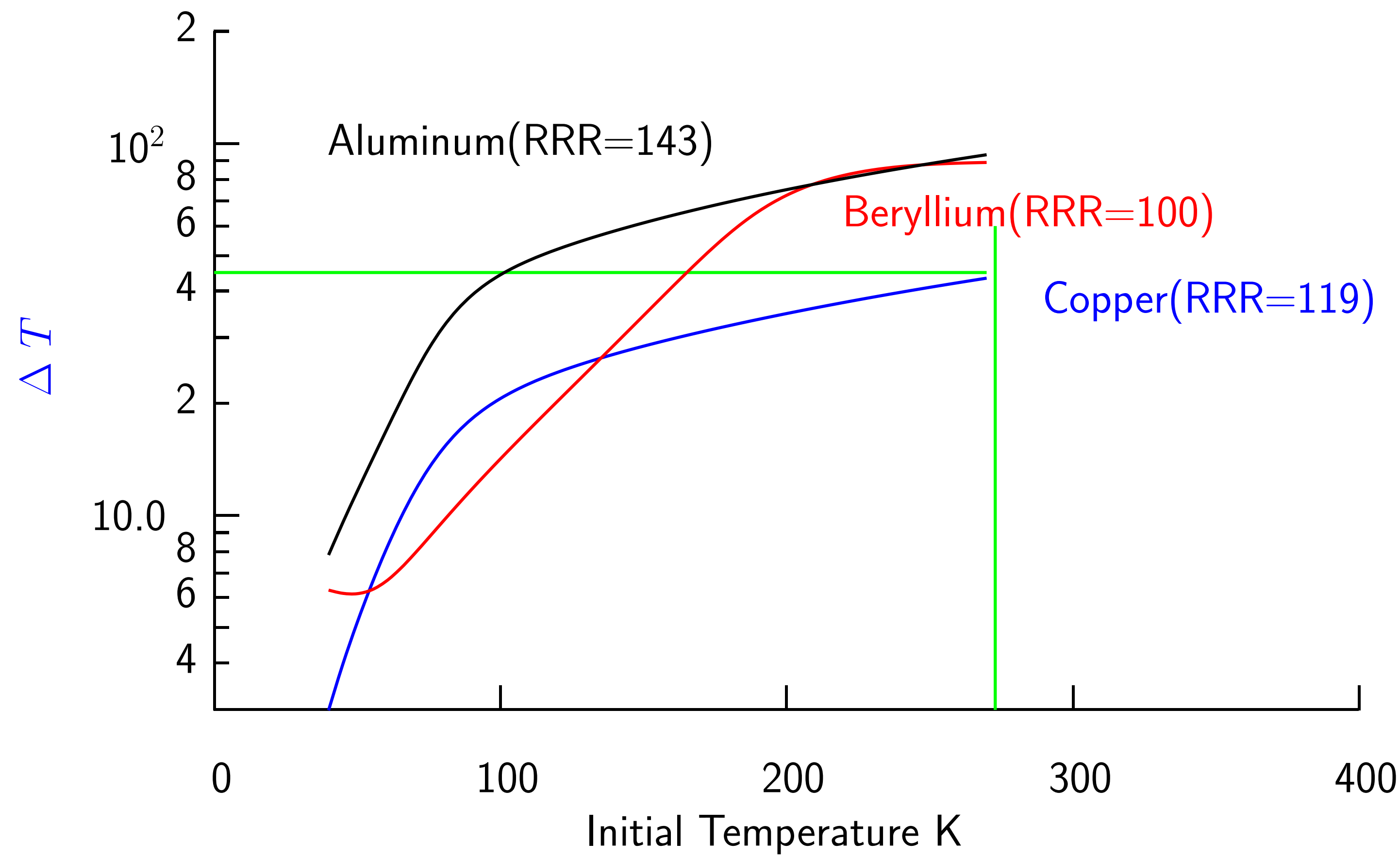
$$T(t) \;=\; T_1 \;+\; \int_{t=0}^{\tau} \left(\frac{k_2\, \mathcal{E}^2\, \sqrt{\mathrm{R(T)}}}{\rho\; \mathrm{C_p(T)}\; \sqrt{\frac{\tau\;\mathrm{K(T)}}{\rho\;\mathrm{C_p(T)}}}} \right) dt$$

where k_2 is a constant, set to give 45 degree rise with SLAC parameters. The resulting strain S is:

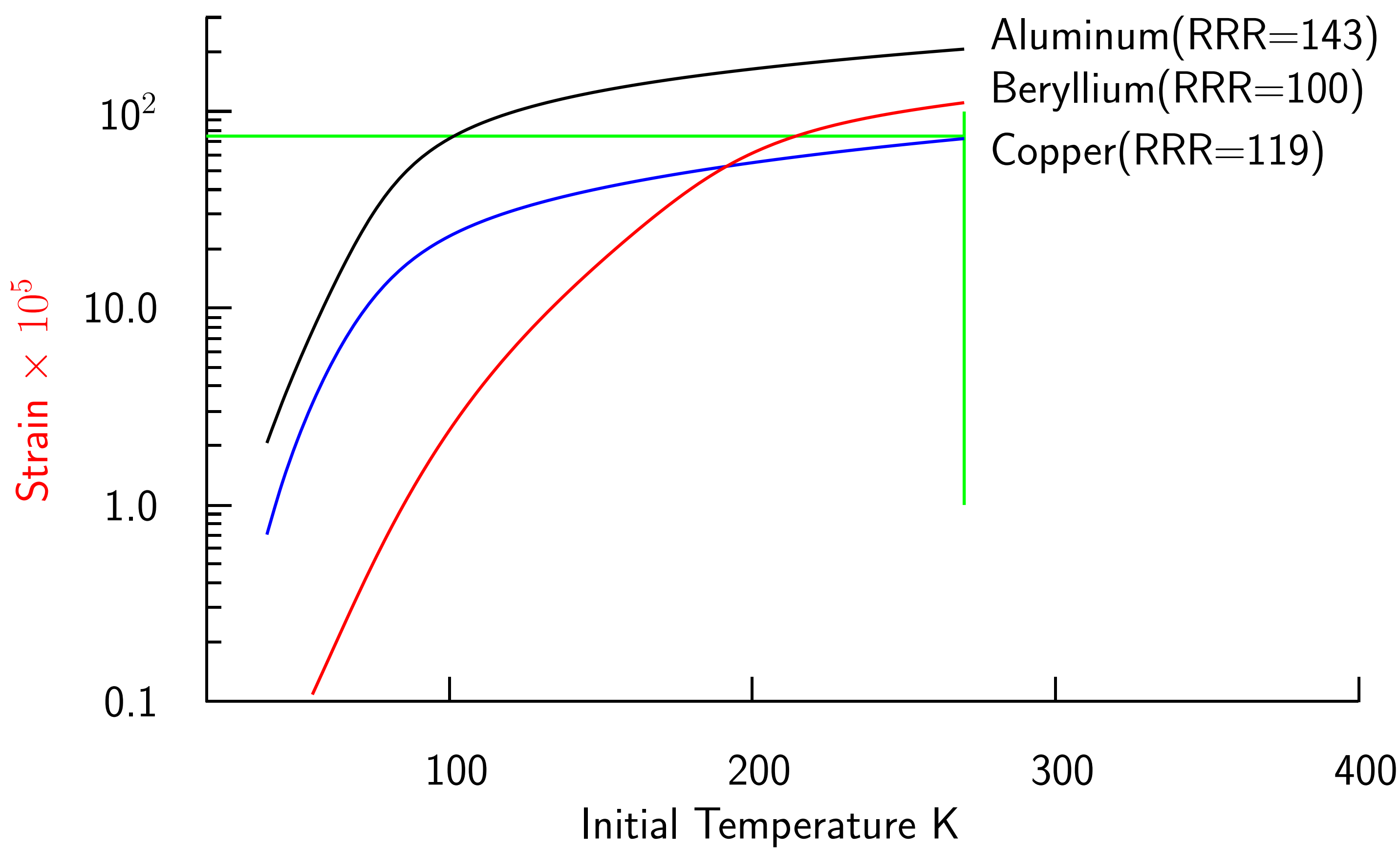
$$S \;=\; \int_{t=0}^{\tau} \alpha(T) \left(\frac{k_2\, \mathcal{E}^2\, \sqrt{\mathrm{R(T)}}}{\rho\; \mathrm{C_p(T)}\; \sqrt{\frac{\tau\;\mathrm{K(T)}}{\rho\;\mathrm{C_p(T)}}}} \right) dt$$

where $\alpha(T)$ is the expansion coefficient.

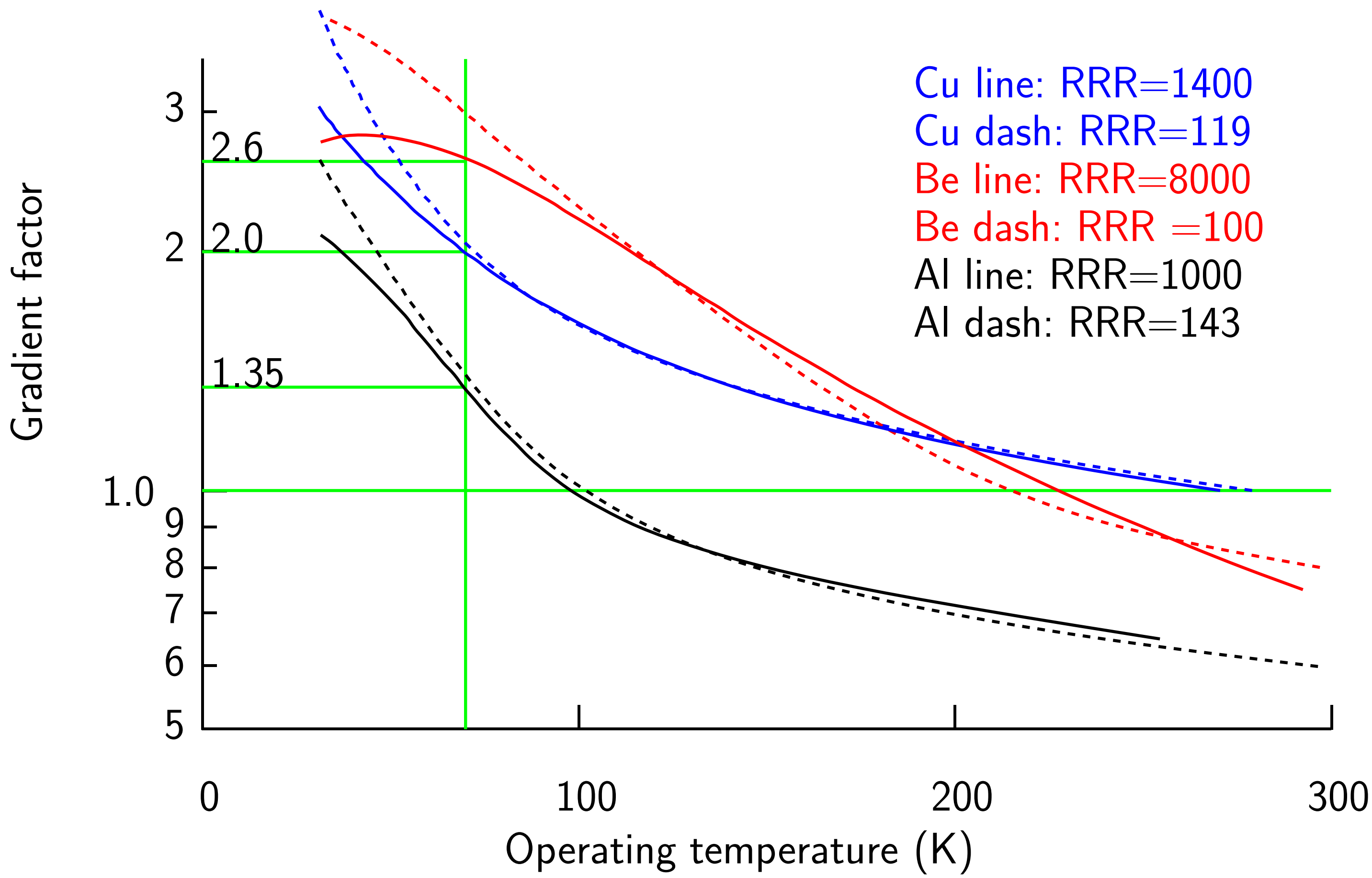
Temperature rises



Strains vs. Temperature



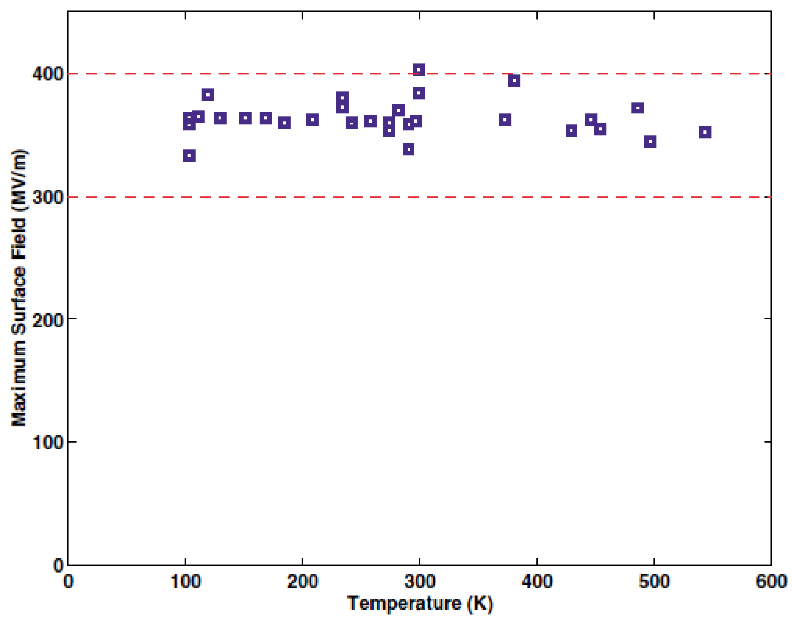
Relative gradients for the same strain

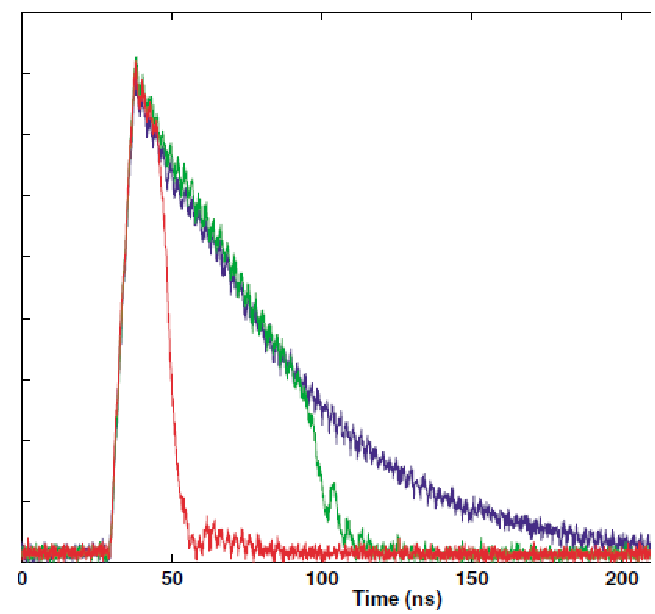


- No advantage of Al of Cu
- Big gain in cooling Cu
- Even greater gain with cold Be

Conflict with CLIC resilts ?[1]

- CLIC observed no temperature dependence on a 30 GHz copper cavity excited by an 8 nsec bunch train
- But their pulse length (8 nsec rise, immediate fall) was much less than:
  a) 1.5 (μsec) as used by SLAC
  a) a normal 3 $\times$ τ fill time, and assumed here
  b) 70 nsec flat top, as required by CLIC





- Sami Tantawi (SLAC) will test a 12 GHz cavity with no surface fields[2]

[1] H. H. Braun et al; Phys Rev Letters; 90, 224801 (2003)
[2] S. G. Tantawi et al; Proc PAC07

Conclusion on rf ohmic heating

- Significant suppression of damage, from cyclical surface ohmic heating, if a Cu cavity is operated at lower temperatures.
- No gain from Aluminum
- No gain from Be at room temperature, but superior at low temperatures
- The gain by cooling Cu will soon be tested at SLAC using their cavity with no surface electric fields
- For high frequency cavities (f $>$ 10 GHz) this should translate into reduced damage or higher operating gradients, especially for longer pulse lengths than used in CERN test

Appendix: Material parameters

- Assume Energy loss dE/dx, density ρ are independent of temperature
- Look at resistivity $R(T)$ for different purities and resulting RRR's $[R(273)/R(4)]$
- Assume Thermal conductivity $K(T) \propto T/R(T)$

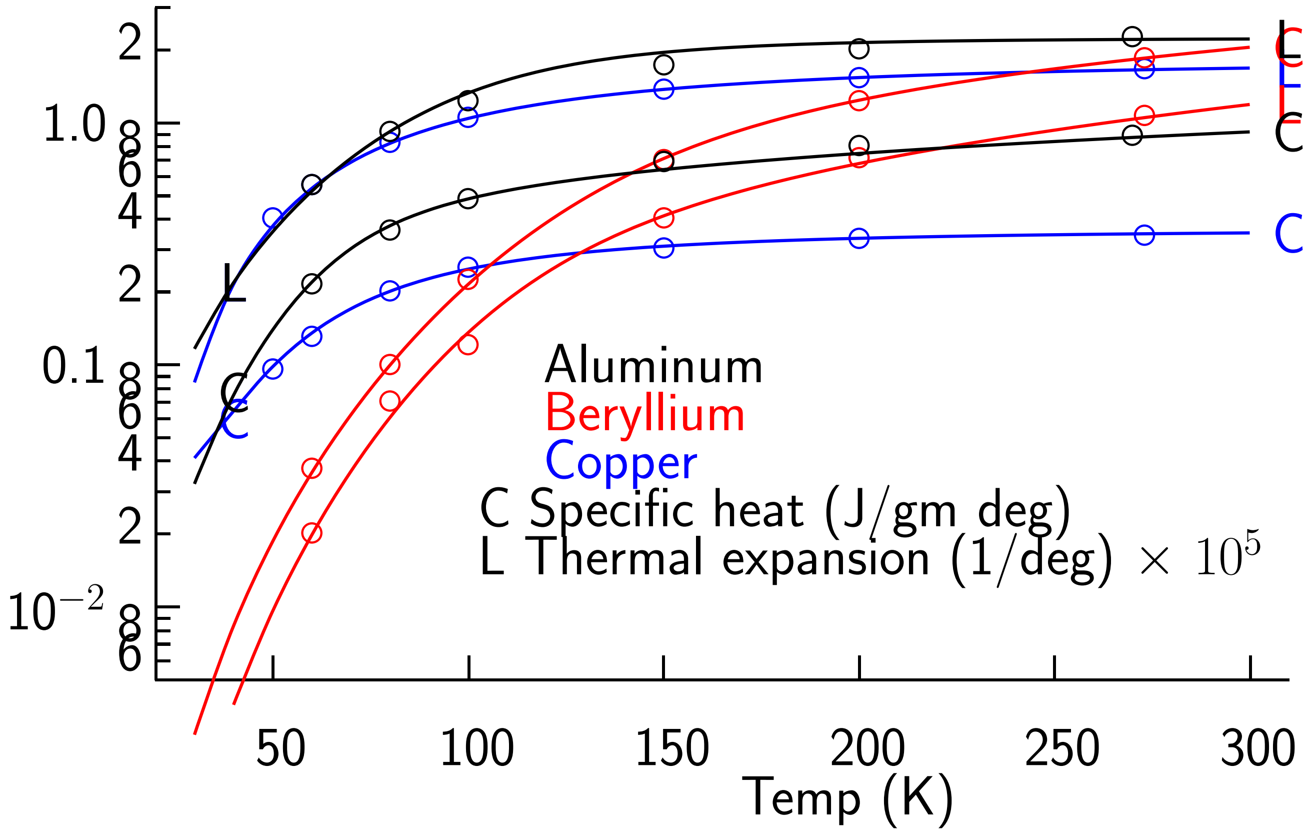
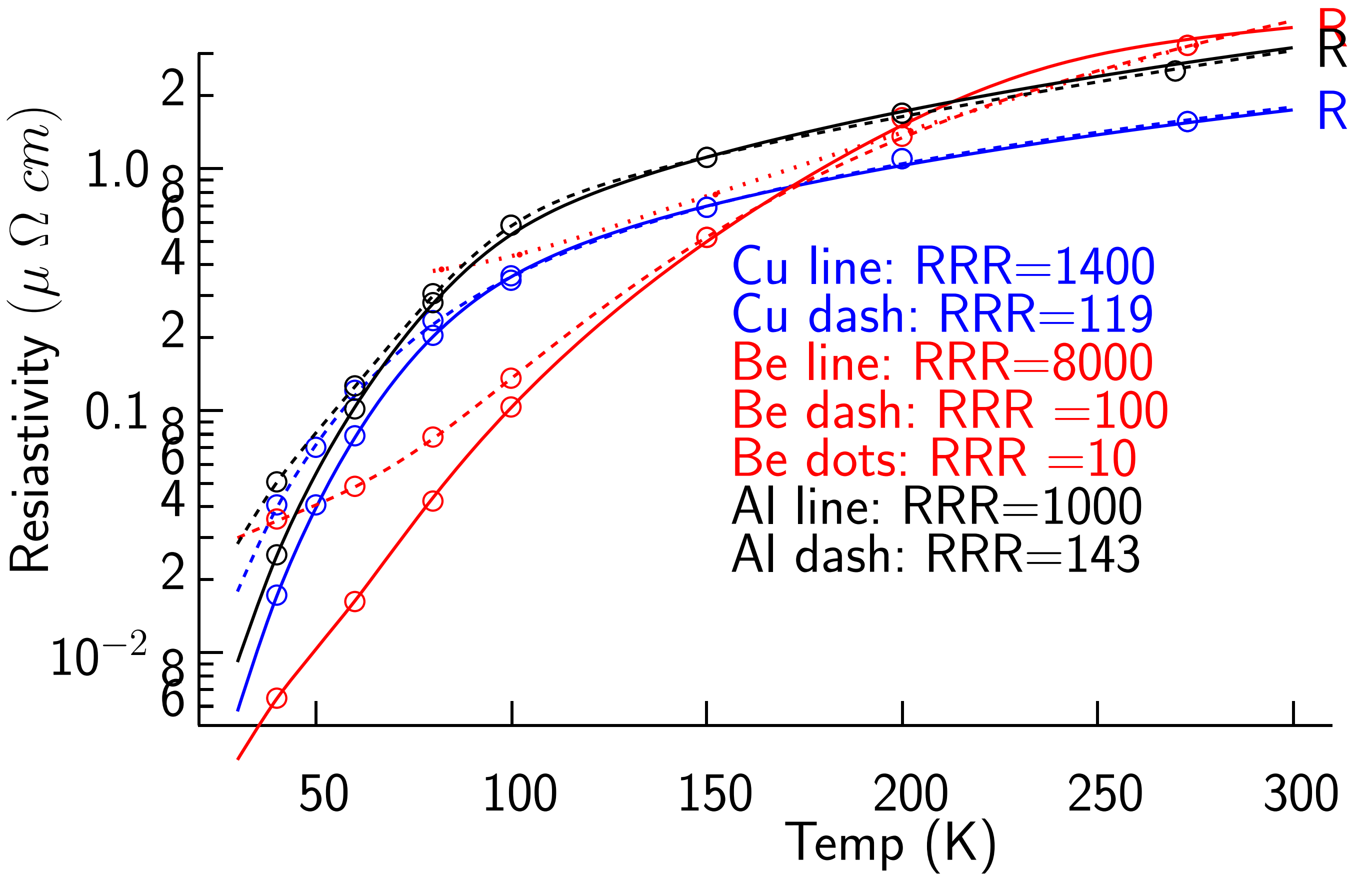


Fig. 1



Resiastivity $(\mu\,\Omega\,cm)$
Temp (K)
Cu line: RRR=1400
Cu dash: RRR=119
Be line: RRR=8000
Be dash: RRR =100
Be dots: RRR =10
Al line: RRR=1000
Al dash: RRR=143
R
R
R
2
1.0
0.1
10^{-2}
50
100
150
200
250
300

Fig. 2

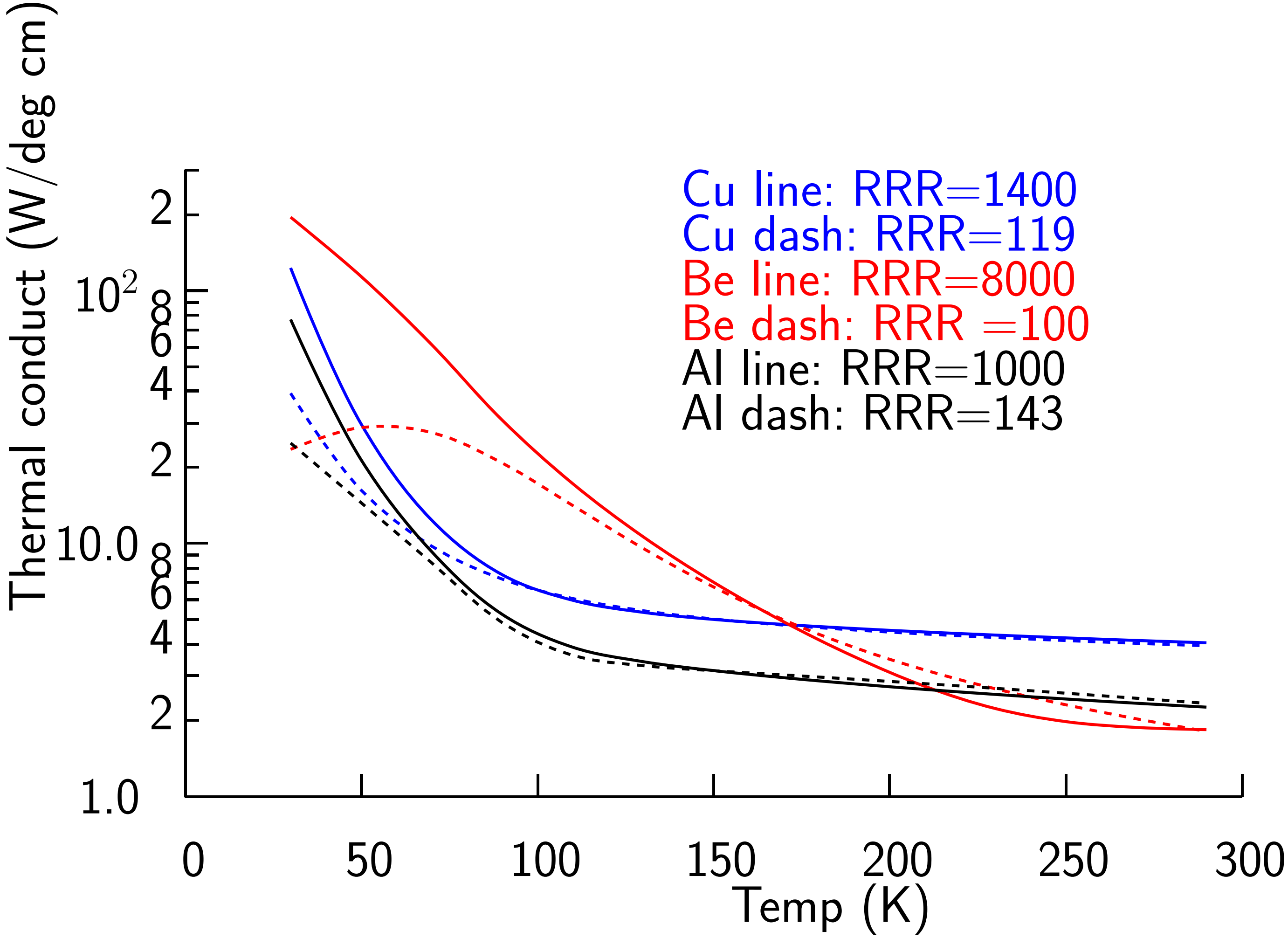

Cu line: RRR=1400
Cu dash: RRR=119
Be line: RRR=8000
Be dash: RRR =100
Al line: RRR=1000
Al dash: RRR=143
Thermal conduct (W/deg cm)
Temp (K)
0
50
100
150
200
250
300
1.0
10.0
10^2
2
4
6
8

Fig. 3

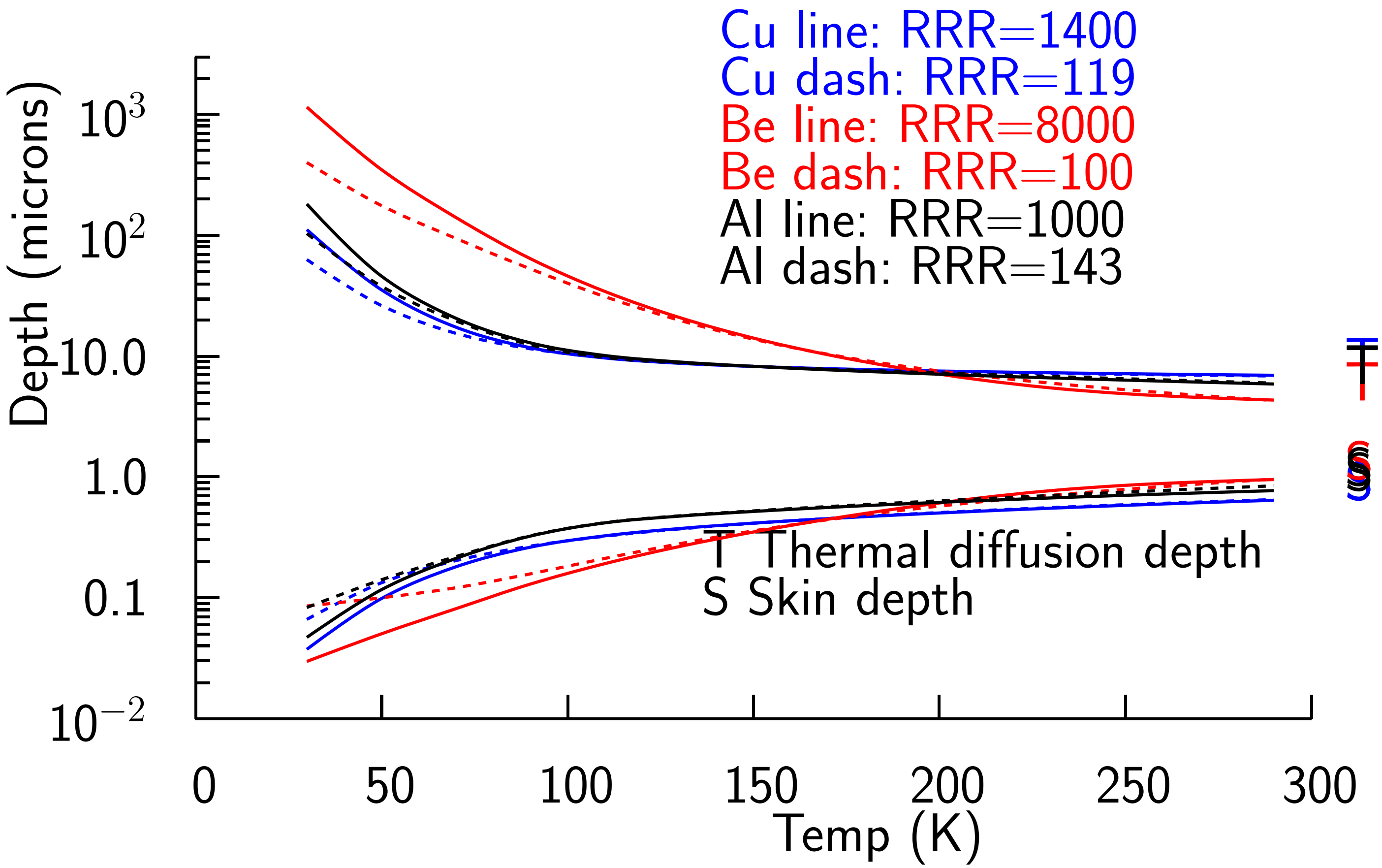

Cu line: RRR=1400
Cu dash: RRR=119
Be line: RRR=8000
Be dash: RRR=100
Al line: RRR=1000
Al dash: RRR=143
T Thermal diffusion depth
S Skin depth
Depth (microns)
Temp (K)
10^3
10^2
10.0
1.0
0.1
10^{-2}
0
50
100
150
200
250
300
T
S

Fig. 4